

Neutrino Astronomy with ANTARES *

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ANTARES is a project aiming at the operation of an underwater detector at a depth of 2.5 km close to Toulon in the South of France. The detector is expected to be completed at the beginning of 2007. The main purpose of the experiment is the detection of high energy neutrinos produced in astrophysical sources. Being weakly interacting, neutrinos could potentially be more powerful messengers of the universe compared to photons, but their detection is challenging. The technique employs phototubes to detect the arrival time and the amplitude of photons emitted by neutrino charged secondaries due to the Cherenkov effect. ANTARES will contribute significantly in the field of neutrino astronomy, observing the Galactic Centre with unprecedented pointing capabilities.

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1. Introduction: neutrino astronomy and telescopes

Neutrinos are considered possible new messengers of the universe since their properties differ from those of photons, that currently provide most information. They could improve our understanding of the sources and mechanisms capable of accelerating cosmic rays up to energies larger than 10^{20} eV, that are observed by extensive air shower arrays. Photons of energies larger than 10 TeV cannot bring information from distances $\gtrsim 100$ Mpc since they interact by pair production with background photons.

A deep connection between high energy γ emissions and ν production exists according to the model of the “beam dump”. Protons or nuclei accelerated by an engine, interact on a gas of matter or photons. These interactions result mainly in neutral and charged pions which decay into

* Presented at XXXIV Int. Symposium on Multiparticle Dynamics, ISMD 2004, Sonoma County, CA, July 30, 2004

photons and neutrinos. This explains the expectation that, if γ absorption could be ignored, observed γ fluxes and ν ones should have almost the same normalization and spectral shape. This should be a power law with spectral index around $-(2 \div 2.5)$, as expected from Fermi acceleration processes.

Gamma-ray experiments are currently providing interesting results and a new era for the observations above 1 TeV has been recently inaugurated by the HESS experiment [1]. The experiment observed TeV photons from the Galactic Centre with 9 standard deviations in only 12 h of observation, reconstructing a spectral index of the differential energy spectrum above 165 GeV of $-2.21 \pm 0.09 \pm 0.15$, in disagreement with CANGAROO [2]. This region is extremely complicated due to the presence of Sgr A*, most probably a super-massive black hole, and of the supernova remnant (SNR) Sgr A East. The measured spectrum could be interpreted as due to purely electromagnetic processes, but also to proton acceleration and photo-meson interactions with ambient radiation or interactions with the plasma close to Sgr A* [3]. Both these last two scenarios imply high energy ν production.

From about 18 h of data, HESS estimated a similar spectral dependence than for the Galactic Centre for the SNR RX J1713-3946. The observed photon spectrum by CANGAROO was pointed out to be explained by π^0 decay and not by electromagnetic processes [4], though the result has been considered controversial since the predicted spectrum seems to exceed the EGRET observed flux from the nearby region. The spectrum measured by HESS does not show the cut-off in the CANGAROO spectrum and it is compatible with EGRET observations. If the ν flux were equal to the one measured by HESS, event rates expected in ANTARES would be < 1 event/yr. Nevertheless, it is clear that the Galactic Centre region is getting more and more interesting for what concerns the possibility of proton acceleration. The observation of this region can be done only from the upper hemisphere using ν -induced muons, that is the topology with the best angular resolution in ν telescopes. Preliminary studies show that ANTARES will perform this observation with unprecedented angular resolution, comparable to recent and forthcoming γ experiments, such as HESS, MAGIC, INTEGRAL, SWIFT and GLAST. These experiments will provide alerts in case of bursting sources, such as gamma-ray bursters (GRBs), and clues to select interesting candidates in order to enhance ANTARES sensitivity.

Other galactic sources, such as fast rotating neutron stars in SNRs, plerions, associations of stars, and magnetars, are foreseen to predict up to hundreds of muon neutrino events in a cubic-kilometer detector and a few events in ANTARES (for a review see [5] and references therein). ANTARES effective area for muons reaches 0.05 km^2 for $E_\nu \gtrsim 10^6 \text{ GeV}$. The most promising models are already constrained by the AMANDA-II limits [8, 9]. This is the case of the micro-quasar model in [6] for what concerns the

persistent source SS433, though this peculiar source is surrounded by a nebula and hence the model could be particularly uncertain.

Extragalactic sources, such as active galactic nuclei and GRBs, if transparent to nucleons, can produce event rates up to from a few to a few hundreds of events in a km^3 telescope. As a matter of fact, if the neutrons can escape sources and produce the UHE protons observed by extensive air shower arrays above 10^{18} eV, an upper limit can be derived as firstly shown in [7] (hereafter W&B limit). Nevertheless scenarios exist that evade the limit by considering other proton spectral dependences than E^{-2} and sources that are not transparent to nucleons (see Ref. [10], hereafter MPR limit). AMANDA-II [8, 9] is already at the level of testing the limit for completely opaque sources in [10], while the W&B flux limit will be tested after 1 yr of operation of the km^3 detector IceCube [11].

It is probable that neutrino detection will allow also to address the problem of the observation of the ultra-high energy cosmic rays (CRs), since these could be produced by the same processes in sources. Other granted high energy ν sources should be CR interactions with the cosmic microwave background and with the galactic interstellar matter (for the former event rates in ANTARES are of the order of a few events per year). Moreover, speculative top-down production processes can be envisaged, where super-massive particles or topological defects decay into neutrinos.

Neutrino telescopes detect the Cherenkov light emitted by charged particles produced in ν interactions by 3-D arrays of optical modules (OMs). OMs are pressure resistant glass spheres containing phototubes (PMTs), located in polar ice or sea/lake water depths in order to reduce the surface μ flux by orders of magnitude. From the times of PMTs hit by the Cherenkov light, tracks can be reconstructed, while the amplitudes allow an energy reconstruction. Neutrino telescopes were originally optimized to detect upward-going muons from ν_μ charged current (CC) interactions. Their direction of flight allows to discriminate atmospheric muons, since ν s are the only atmospheric shower secondaries capable of crossing the Earth. Since the ν cross-sections and the μ range increase with energy, the effective target mass for ν interactions becomes larger with energy. As a matter of fact, the larger the energy the better the performances of this technique, up to a saturation that depends on the detector dimensions. Moreover, for $E_\nu \gtrsim 10$ TeV the muon has the same direction of the parent neutrino allowing to point sources.

In view of recent results on neutrino oscillations, it is now considered important to detect other flavor neutrinos. Flavor ratios at sources from meson decays, in the hypothesis that the environment density is such that all muons decay, are $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 2 : \lesssim 10^{-5}$ [12]. In light of solar and atmospheric ν results and of constraints from reactor experiments,

oscillations through baselines larger than tens of kpc would lead to $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$. Since the ν cross section increases with energy, CC interactions during propagation through the Earth prevent ν_μ and ν_e from reaching the detector (unless for ν_μ the muon range is larger than the distance of the ν vertex to the detector). The Earth shadowing becomes important above 1 PeV and neutrinos can reach the detector only from the horizon or from the upper hemisphere. Hence for UHE ν detection it is necessary to have good efficiencies in reconstructing horizontal events, to use energy estimators to suppress the atmospheric μ background, and discriminate showering events inside the instrumented region from crossing atmospheric μ tracks. The case of tau ν s is peculiar: they are never absorbed during propagation through the Earth, though they loose energy, since they regenerate in τ decays [12]. They can produce background free topologies, such as the 'double bang' events, where the shower from the ν vertex and the shower from the electronic and hadronic τ decay channels are connected by a τ track, long enough to separate the showers. These interesting events, that would prove ν oscillations in an astrophysical beam, are expected to be very rare, depending on the assumed spectrum, due to the fact that a τ track is > 50 m for $E_\tau \gtrsim 1$ PeV).

2. The ANTARES project

The ANTARES Collaboration was formed in 1996 and comprises physicists, astronomers, engineers and sea experts from France, Germany, Italy, the Netherlands, Russia, Spain and The United Kingdom. The installation of the detector has started in a 2.5 km deep site about 40 km off-shore Toulon (42°50'N, 6°10'E). The set-up of the telescope is shown in Fig. 1. Twelve lines form an octagon with average distances of about 65 m. Being 450 m high, they are kept taut by buoys at the top end and by anchors at the bottom. The first 100 m from the bottom of the line are not instrumented, so that OMs are far enough from seabed mud and to have additional water volume where the Cherenkov light can be produced. Each line is connected to a junction box (JB), distributing data and power from/to the detector from/to the shore station through the electro-optical cable (EOC). Both the JB and the EOC are already installed and performing well since Oct. 2001 and Dec. 2002, respectively. Each line is instrumented with 25 storeys separated vertically by 14.5 m, holding 3 OMs, each containing a 10" 14 stage Hamamatsu R7081-20 phototube (PMT). The 3 PMTs are mounted at 45° from the vertical looking downwards. As a matter of fact, the OM transparency reduction is negligible for surfaces exposed below the horizon [13]. OMs, that have to resist 260 bars during normal operation, are transparent in the 400-500 nm wave-length region. They include a μ -metal cage

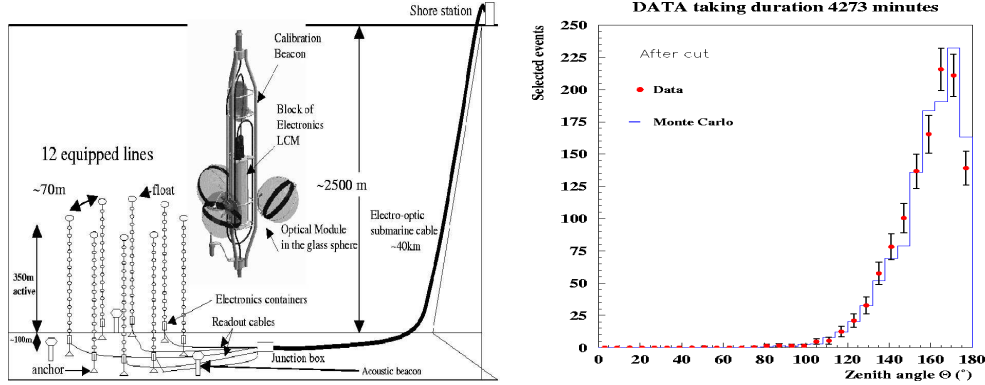


Fig. 1. **On the left:** Layout of the ANTARES detector. The detail of a storey is shown. **On the right:** reconstructed atmospheric μ angular distribution from Line 5 data. The areas of the curves are normalized to each other.

preventing the Earth magnetic field to deflect electron paths [14] and a blue LED for time calibrations. At the moment of writing (Oct. 2004), 250 OMs of the 900 have been completed.

The main specifications that ANTARES PMTs must satisfy are: a transit time spread (TTS) of less than 3 ns (FWHM), a peak to valley ratio larger than 2, a dark count of less than 20 kHz for a 0.25 photoelectron (pe) threshold, and a gain larger than $5 \cdot 10^7$. Laser calibrations in a dark room using a prototype line made of 5 storeys have shown that, after corrections of clock delays between consecutive storeys, the achievable timing resolution is $\sigma \sim 0.9 - 1.2$ ns. Each storey contains a local control module, a titanium cylinder containing the electronics. The digitization of the PMT signals is done by the Analogue Ring Samplers (ARS), ASIC full custom chips. Signals are processed according to a single photoelectron mode, that provides the time stamp and charges, and a waveform mode for $\sim 2\%$ large amplitude or complex signals by waveform digitizers (1 GHz sampling). The motherboard for each PMT is equipped with 3 ARS and 2 of them are activated in turn to reduce dead time. The digitized data will be sent to shore through optical fibers at a rate of ~ 1 GB/s for further processing with a PC farm. Online filters, based on clustering algorithms that rely on time correlations between hits through velocity of light in water, will reduce the amount of data by a factor of $\sim 10^3$. As a matter of fact, this will allow the rejection of most of the background data due to ^{40}K decays and bioluminescence. The data filter efficiency for upgoing ν events, under continuous improvements, increases with energy and is of the order of 50% at 1 TeV and 70% at 10 PeV. It can be dramatically improved, especially at low

energies, when the directional information is used. This is the case of GRBs for which ANTARES will receive alerts from the GCN network of satellites and of candidate sources that can be followed in dedicated periods.

Since lines move in water, the position and orientation of OMs must be monitored. Relative positioning of storeys, which should be accurate at the 0.5 ns level, is provided by a system of acoustic beacons at seabed and hydrophones in storeys. The orientation is determined through compasses and tiltmeters in the electronics container. The PMT TTS will be calibrated using the LEDs in the OMs, an optical beacon each 5 storeys and a laser beacon at the bottom of some of the strings. The absolute timing will be ~ 1 ms accurate by correlating the time provided by the GPS system to the internal clock, a 20 MHz high accuracy electrical signal generated on-shore and converted into an optical signal distributed to the detector.

ANTARES has done many tests and sea campaigns for the site qualification. This phase includes the deployment of a test line with 7 PMTs in Nov. 1999 (Line 5) at 1.2 km depth, that has reconstructed atmospheric muons requiring a 5-fold coincidence. Their zenith angle distribution is shown in Fig. 1 (on the right). The shape is in agreement with the Monte Carlo. In 2003 a prototype line with 5 storeys and a reduced version of the final instrumentation line devoted to environmental parameter monitoring were operated for a few months and recovered. Both lines were successfully installed within a few meters from their nominal positions and connected to the JB, proving the feasibility of marine operations. Measurements of the heading of storeys have shown that the line moves as a rigid body. Beside the successful operation of these lines, a few problems occurred and remedies have been found for the forthcoming lines. The failure in the clock transmission prevented the data taking at nanosecond precision level. Nevertheless, the counting rate monitor has allowed taking optical background data for a period of ~ 100 d. Large and short lived peaks of a few seconds due to light emitting animals have been detected over a baseline of about 60 kHz due to ^{40}K decay and bacteria. This baseline is variable and can increase up to values of 200 kHz. Correlations of this background to sea currents, e.g. the water rotation due to the Coriolis force, and to storey heading have been demonstrated.

2.1. Physics studies

The parameters that best describe neutrino telescope performances are the effective volume and the neutrino effective area, that are deeply connected (see Fig. 2). They need to be expressed as a function of neutrino energy in order to have a unique definition of the energy for different experiments and different topologies of events. As a matter of fact, secondaries

such as muons from ν_μ CC interactions loose energy during propagation outside and in the instrumented region, hence their energy cannot be uniquely defined. The effective volume of neutrinos is the volume of a 100% efficient detector for observing ν interactions that would obtain the same event rate as ANTARES for a given interaction rate (that depends on the ν flux, the target medium and the cross-section): $V_{eff} = \epsilon V_{gen}$, where V_{gen} is the volume where neutrino CC interactions can produce secondaries than can emit detectable Cherenkov light (for ν_μ it depends on the muon range). This definition includes the tracking and selection requirements: $\epsilon = \frac{N_{sel}(E_\nu, \Omega)}{N_{gen}(E_\nu, \Omega)}$, where N_{gen} is the number of generated events in the generation volume V_{gen} and N_{sel} is the number of selected events. The ν effective area is the sensitive area 'seen' by ν 's producing detectable μ 's when entering the Earth:

$$A_\nu^{eff}(E_\nu, \Omega) = V_{eff} \cdot N_A \rho \sigma_\nu(E_\nu) \cdot P_{Earth}(E_\nu, \Omega), \quad (1)$$

where P_{Earth} is the absorption probability through the Earth, and $1/(N_A \rho \sigma_\nu)$ is the interaction length in the matter of the generation volume. This is a function of the energy and of the local angles and it allows the calculation of event rates for a ν model predicting a spectrum $\frac{d\Phi}{dE_\nu d\Omega_\nu}$:

$$N_\mu = \int \int dE_\nu d\Omega_\nu A_\nu^{eff}(E_\nu, \Omega_\nu) \frac{d\Phi}{dE_\nu d\Omega_\nu}. \quad (2)$$

Given this definition, it is understandable why the dimension of this quantity is orders of magnitude lower than the geometrical dimensions of the array. Simply such huge detectors are reduced to areas of the order of tens of m², due to the weakly interacting properties of neutrinos. The area being strongly energy dependent, detectors respond in different regions to ν 's with different spectra: the harder the spectrum the highest is the mean energy of the corresponding detectable events (e.g. ~ 100 GeV for typical $E^{-3.6}$ atmospheric ν spectra, ~ 10 TeV for typical E^{-2} cosmic ν spectra).

Another fundamental parameter for point-like source searches is the angular resolution for tracks $\Delta\theta$, since the signal to noise ratio is given by:

$$S/\sqrt{N} \propto \sqrt{AT}/\Delta\theta, \quad (3)$$

where A is the effective area and T the detection time. The angular resolution as obtained by ANTARES simulations is shown in Fig. 3 (on the left). The plot shows the median angle between the ν source and the reconstructed muon and the 'intrinsic angular resolution', that is the angle between the 'true' muon and the reconstructed one. Its limiting value is $\sim 0.2^\circ$ for $E_\nu \gtrsim 10$ TeV. The sensitivity of ANTARES for 1 year of data taking as a function of declination for two different methods of searches for

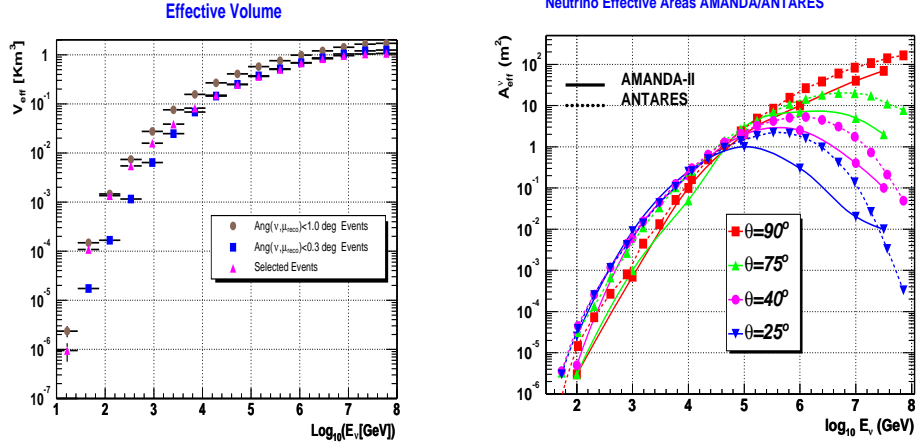


Fig. 2. **On the left:** the ANTARES effective volume for $\nu_\mu + \bar{\nu}_\mu$ vs ν energy. The triangles indicate the volume after quality requirements are applied to the reconstruction algorithm. In order to understand the pointing capabilities after this cuts, the squares indicate the effective volume that would be obtained when the angle between the simulated ν and the reconstructed μ is $\leq 0.3^\circ$. While at low energy the difference between the two curves is due to the kinematic angle of the $\nu - \mu$ interaction, at energies $\gtrsim 10$ TeV it is dominated by the intrinsic angular resolution. For searches where also time constraints can be used to reject the atmospheric muon background looser cuts can be applied, corresponding to a larger A^{eff} (dots for the 1° cut). **On the right:** Comparison of the ANTARES neutrino effective area (dashed lines) with the AMANDA-II one [8] (solid lines) for zenith angles. The decrease of the area in the vertical region (inverted triangles) compared to the horizontal one (squares) at energies $\gtrsim 100$ TeV is due to the shadowing effect of the Earth due to the cross-section increase with energy.

point-like sources is shown in Fig. 3 (on the right), where it is compared to other experiments. Studies on the sensitivity of ANTARES to a diffuse muon neutrino flux from populations of sources have brought to the result given in Fig. 4, where it is compared to other experiments. In this case the best estimator of the energy between those tested has resulted to be the number of hit PMTs, that is used to make a high energy cut to reject atmospheric muons and neutrinos. This possibility is due to the steeper spectrum of atmospheric fluxes compared to fluxes from sources.

3. Summary and Outlook

ANTARES will observe the Southern hemisphere sky using neutrinos. It will complement the detectors at the South Pole and represents an im-

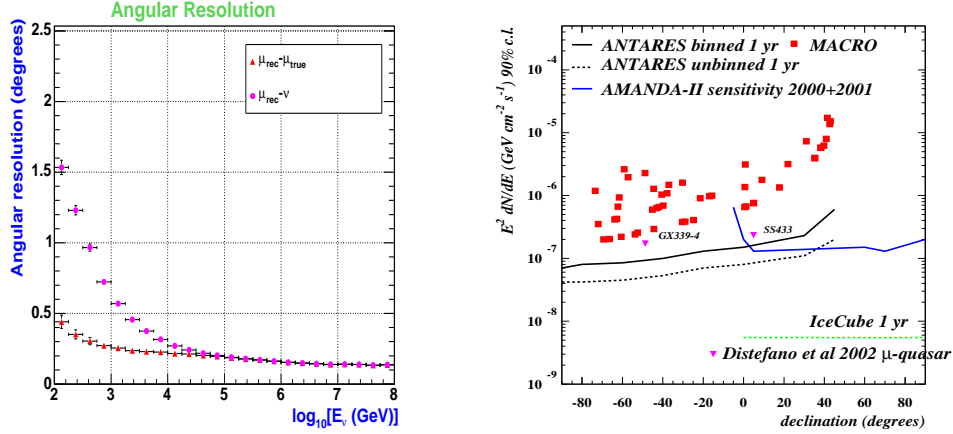


Fig. 3. **On the left:** ANTARES expected angular resolution vs ν energy. The dots represent the median angle between the simulated ν and the reconstructed μ direction (that is the pointing capabilities for a neutrino source), while the triangles are the median of the angle between the simulated muon and the reconstructed one (the intrinsic angular resolution). **On the right:** Upper limits (90% c.l.) on E^{-2} neutrino fluxes as a function of the source declination for MACRO (squares) [17], expected sensitivity of AMANDA-II corresponding to 2000-1 data [9], IceCube [11] and ANTARES [18] (for a search method using a grid in the sky and an unbinned method based on likelihood ratio). AMANDA and IceCube lines cover the upper hemisphere region since upgoing ν events are used. The triangles indicate the expected ν flux from two persistent micro-quasars as calculated in [6]. The flux for SS433 is excluded by AMANDA and after 1 yr of ANTARES data.

portant step to acquire the proper know-how to deploy a km^3 kilometer detector in the Mediterranean. The first line of the detector is planned to be deployed and connected to the junction box in the summer of 2005. In the meanwhile, two more lines will be deployed. The MILOM combines a storey with optical modules, calibration devices (laser, LED beacons and acoustic positioning modules), and instruments for the monitoring of optical and mechanical environment of the site. The so-called Line zero, with 25 storeys but no PMTs inside glass spheres, will allow to realistically test the electro-mechanical cables and all the containers. The assembly and test of both lines will validate the final line integration procedure.

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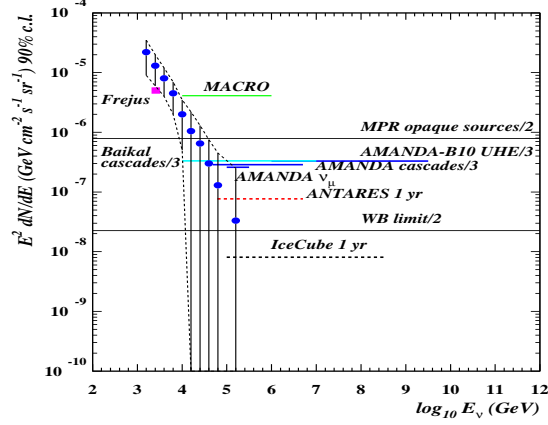


Fig. 4. 90% c.l. limits on diffuse E^{-2} fluxes of $\nu_\mu + \bar{\nu}_\mu$ in the hypothesis of ν oscillations as measured by AMANDA-II [9], Baikal [15] and MACRO [16]. Limits for other flavors than ν_μ (cascades) have been divided by the number of contributing flavors. Also the expected sensitivities for ANTARES and IceCube [11] are shown. Dots are the measured atmospheric ν flux by AMANDA-II [8].

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